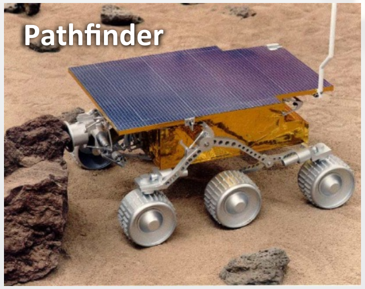
EDL trajectory and atmospheric reconstruction



Approach pioneered by Alvin Seiff in 1960's

Engineering return

Validation of capsule and trajectory design tools for a safe and accurate landing. Both for planetary entry and Earth re-entry.

which environment is producing what we measure?

Scientific return

High resolution and range versus remote observations

Atmospheric state $\rho\infty$ $p\infty$ $T\infty$ to constrain atmospheric models

Atmospheric gravity waves and thermal tides

[IPPW-9 F. Ferri et al. yesterday]

Approaches to EDL atmospheric reconstruction

Classical approach: from the IMU's

Inertial Measurement Units were installed on all Mars landers: accelerometers and sometimes gyroscopes

Density from acceleration and drag coefficient $\rho_\infty(h) = \frac{2m\cdot|a_{aero}|}{C_D\cdot A_{ref}\cdot|v_{rel}|^2}$

Pressure from hydrostatic equation $p_\infty(h) = p_\infty(h_0) - \int_{h_0}^{h} g\cdot\rho_\infty\cdot dh$

Temperature from ideal gas law $T_\infty(h) = \frac{\mu\cdot p_\infty}{R\cdot\rho_\infty}$

In general, C_D depends on Mach, Reynolds numbers and aerodynamic flow angles.

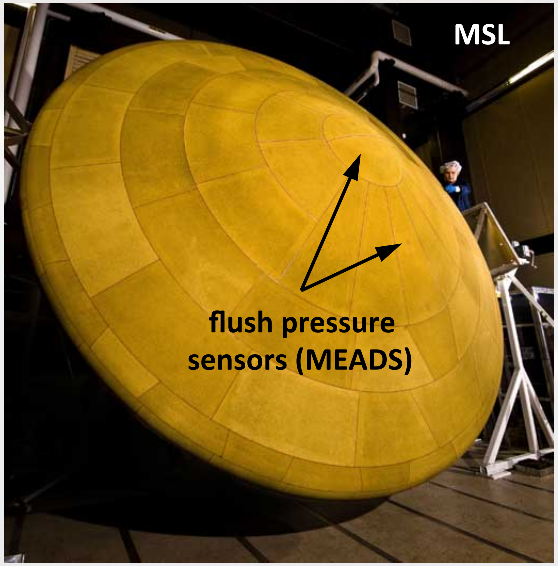
Drag coefficient strongly limits accuracy

Approaches to EDL atmospheric reconstruction

Complementary data: heat shield instrumentation

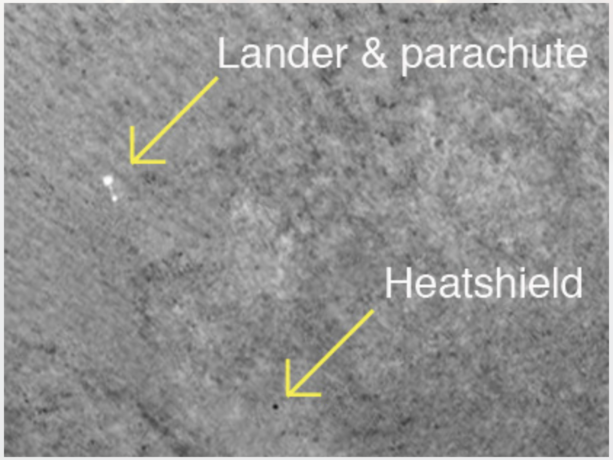
NASA Mars Science Laboratory (MSL) and ESA ExoMars EDL Demonstrator (EDM) heat shields are equipped with a grid of pressure and temperature sensors.

→ **Flush Air Data System (FADS)** retrieves true relative flow direction (including winds) and free stream dynamic pressure and density using a **heat shield pressure model**



Presentation overview

Artist rendition of Phoenix landing on Mars



1. **Revisit IMU trajectory and atmospheric reconstruction for Mars Phoenix**

   Ballistic entry with 5.6 km/s entry velocity at 146 km

   both accelerometers and gyroscopes at 200 Hz

2. **Atmospheric reconstruction from complementary heat shield instrumentation (pressures)**

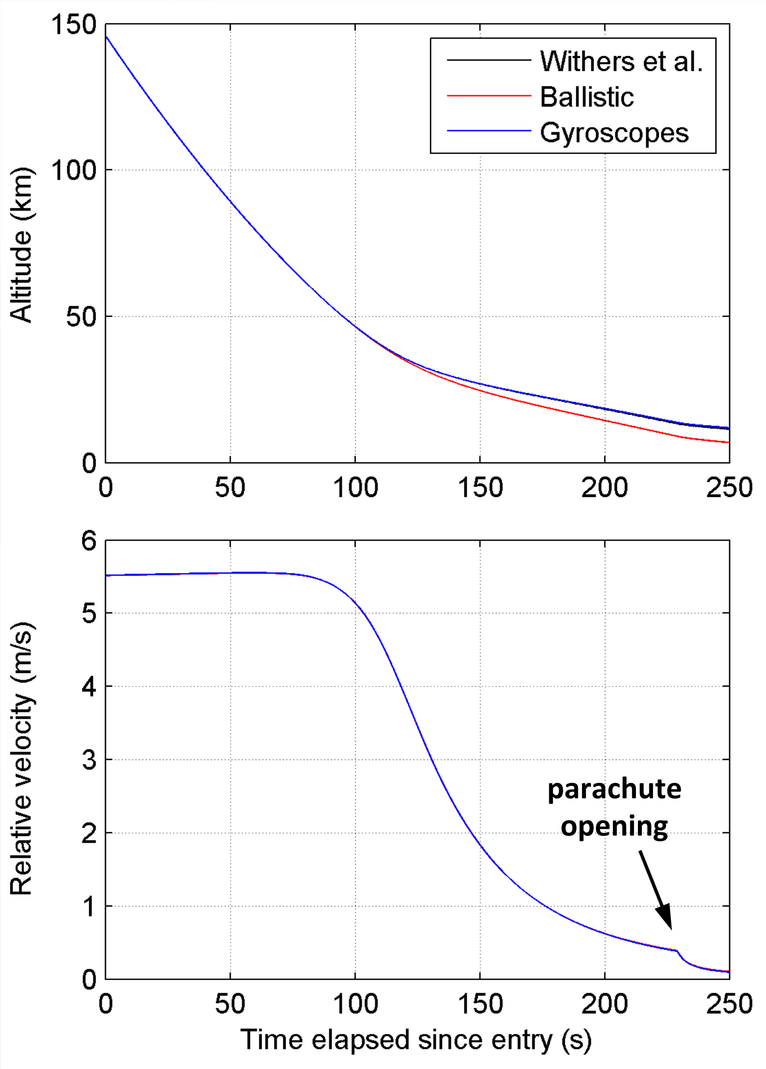
   Hypothetical pressure sensors on Phoenix heat shield

   Newtonian flow model to simulate wall pressures, calculate back using a least-squares solver

   Investigate atmospheric winds

← Phoenix descent observation by the MRO HIRISE camera orbiting Mars

Phoenix IMU trajectory reconstruction



Integration of IMU data

From entry state at 146 km to parachute opening

Heading by assuming a ballistic trajectory (only accelerometers) **or** use accelerometers + gyroscopes

Results

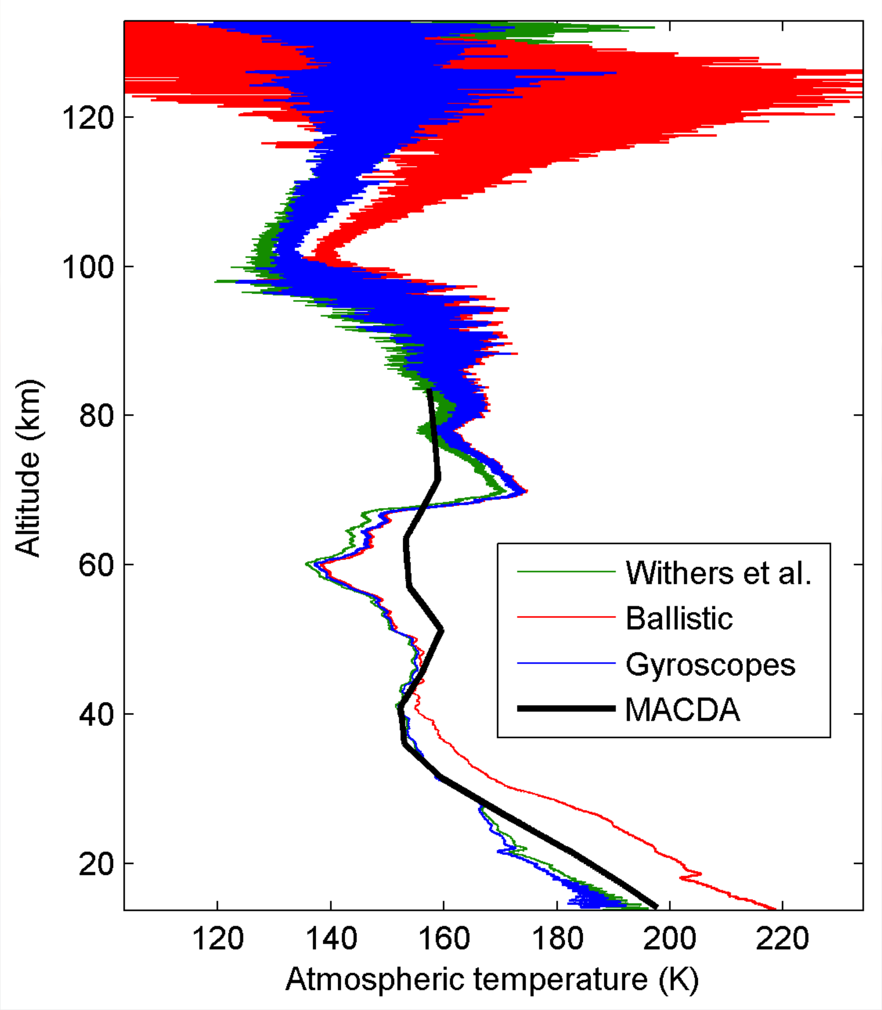
Gyroscope reconstruction matches findings in literature. Positive angle of attack reconstructed.

[Withers et al. 2010]
Phoenix special issue J. of Spacecraft & Rockets 2011:
[Desai et al.] and [Blanchard et al.]

	Desai et al.	This study	3-σ RMS
Time since entry	227.8 s	228.0 s	± 0.000 s
Altitude	13.3 km	13.9 km	± 3.4 km
Relative velocity	387.6 m/s	387.9 m/s	± 42 m/s
Total angle of attack	4.73 deg	4.65 deg	± 4 deg

Reconstructed trajectory conditions at parachute opening (heading from gyroscopes)

IMU atmospheric profiles reconstruction



Results

Temperature profile matches previous results **[Withers et al. 2010]**

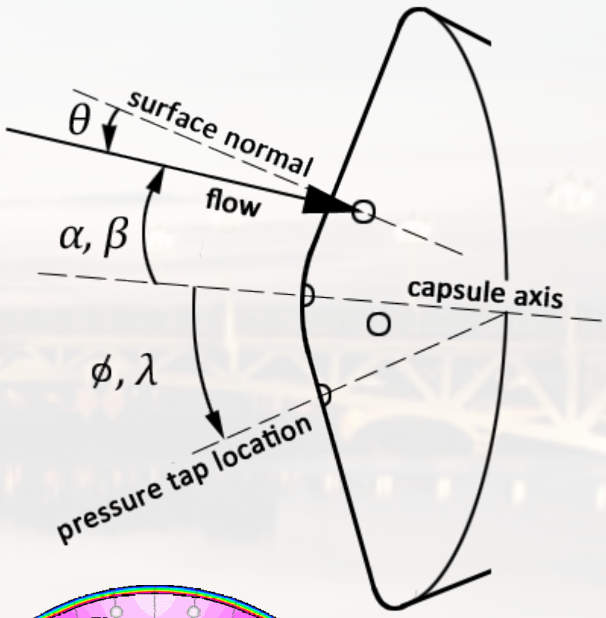
Mars Analysis Correction Data Assimilation (MACDA) using Oxford Global Circulation Model and MCS data. Calculated along our reconstructed Phoenix trajectory.

Assuming a ballistic trajectory strongly affects atmospheric profiles, mainly through altitude in the hydrostatic pressure equation

→ **IMU's without gyroscopes don't reconstruct atmospheric profiles well**

Hypothetical heat shield pressure data using Phoenix IMU reconstructions

Phoenix trajectory and atmospheric reconstruction (accels + gyroscopes) to represent "**truth" values**



Simulated heat shield pressures

Simulate pressures at 7 pressure taps, using the same layout as MEADS on MSL

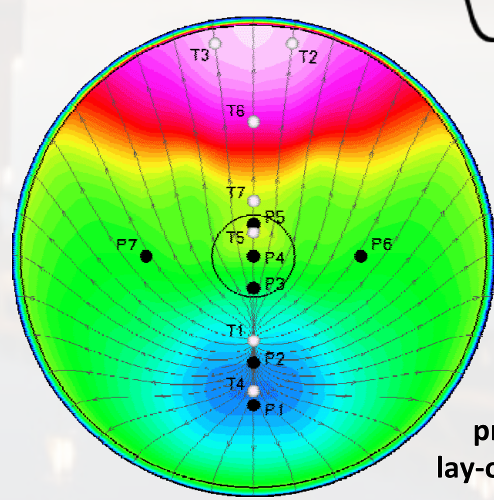
using modified Newtonian flow pressure model:

$$pwall=(p_{tot}-p\infty)\cdot cos(\theta)^2+p\infty$$

with $cos(\theta)^2=f(\alpha,\beta,\lambda,\phi)$

Reconstruct from simulated pressures

Iterative least squares solver reconstructs flow direction (aerodynamic angles α and β) and static and dynamic pressures p_{tot} and $p\infty$ from the simulated $pwall$



MEADS pressure tap lay-out [nasa.gov]

Two ways to calculate density from heat shield instrumentation

From the dynamic pressure

$$\rho_\infty = 2\, p_{tot} - p_\infty / |v_{rel}|^2$$

Dynamic pressure $q_\infty = p_{tot} - p_\infty$ from heat shield, velocity from trajectory reconstruction

From the static pressure

$$\rho_\infty = -1/g(h)\ \partial p_\infty / \partial h$$

Hydrostatic equation in differential form

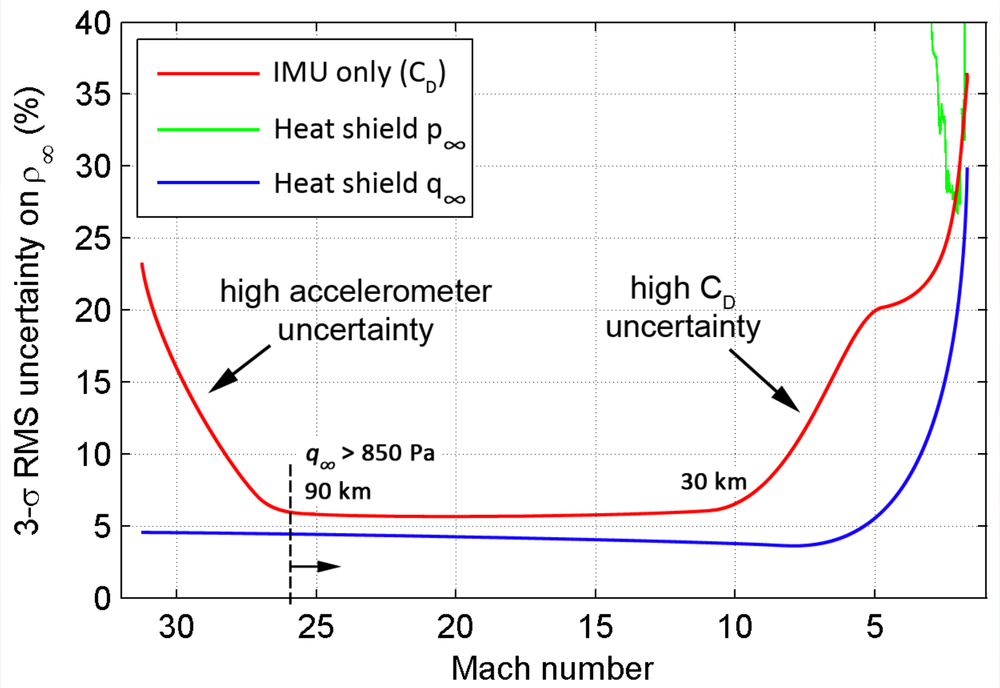
Caution: differentiation is sensitive to noise and p_∞ is difficult to obtain accurately from heat shield measurements as $p_{tot} \gg p_\infty$

Comparison of density calculation methods

RMS uncertainty

Uncertainties on all inputs were estimated **except on pressure model!**

The simulated p_{wall} have 3-σ uncertainties of ±0,5% through entire EDL, based on Monte Carlo analysis for MEADS MSL from $q\infty >$ 850 Pa **[Karlgaard et al. 2009]**



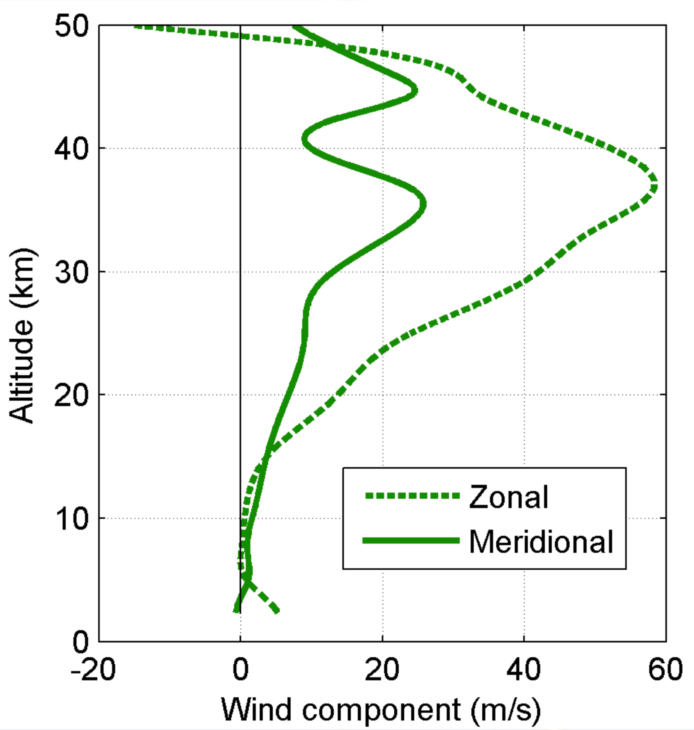
Atmospheric density from the heat shield pressures is more accurate, especially for 10 > Mach > 5

Differential method off the scale...

→ **improvement using heat shield pressures, given an accurate pressure model!**

Atmospheric winds during entry phase

MACDA (Oxford GCM) wind profile



Can atmospheric winds be reconstructed using the heat shield pressure instrumentation?

Horizontal wind profiles from Oxford GCM/MCS model (MACDA: Mars Analysis Correction Data Assimilation)

Implemented assuming unaffected trajectory

in the inertial planet frame, subtract wind from inertial velocity to obtain relative velocity:

$$v_{rel} = v_{inert} - v_{\Omega\, atm} - v_{wind}$$

subsequently, relative flow angles change:

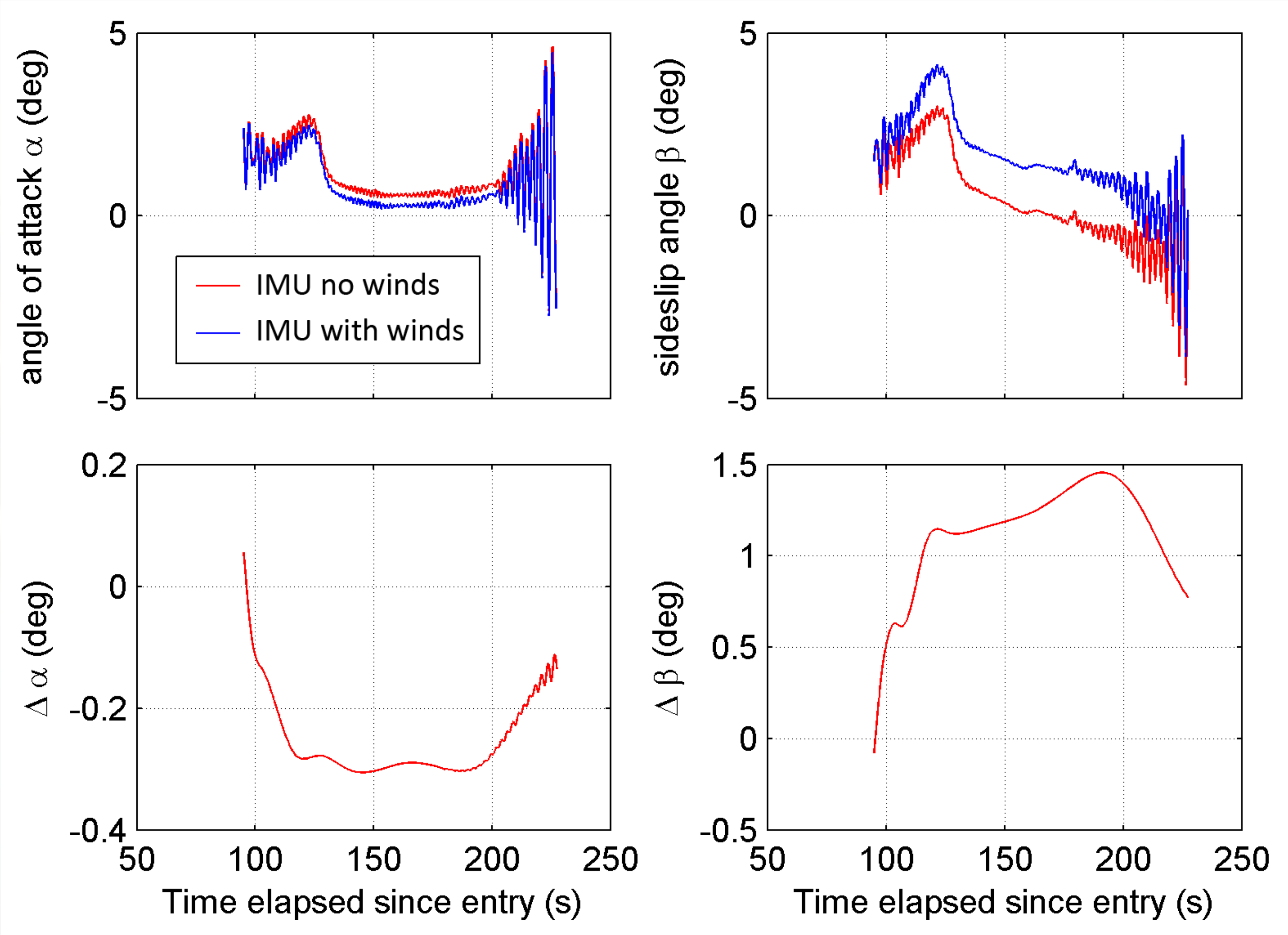
$$\alpha = \tan^{-1}(v_{y\,rel} / v_{z\,rel})$$

$$\beta = \sin^{-1}(v_{x\,rel} / |v_{rel}|)$$

←

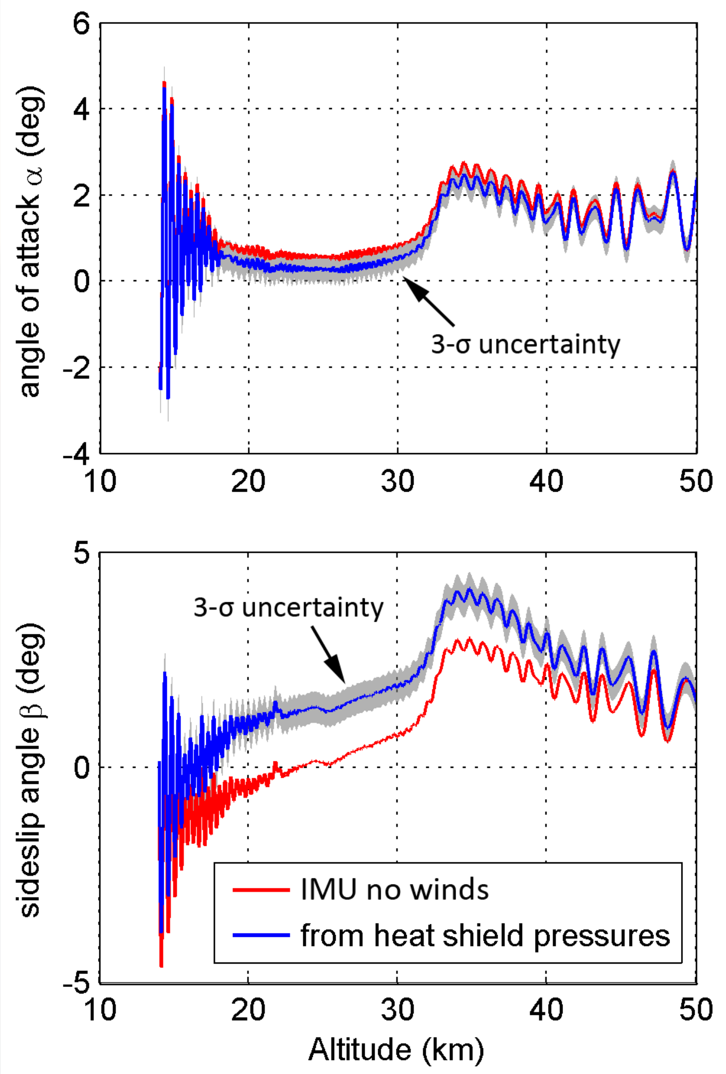
update simulated heat shield pressures

Change in flow angles due to modeled winds



now use the blue flow angles to simulate heat shield pressures again

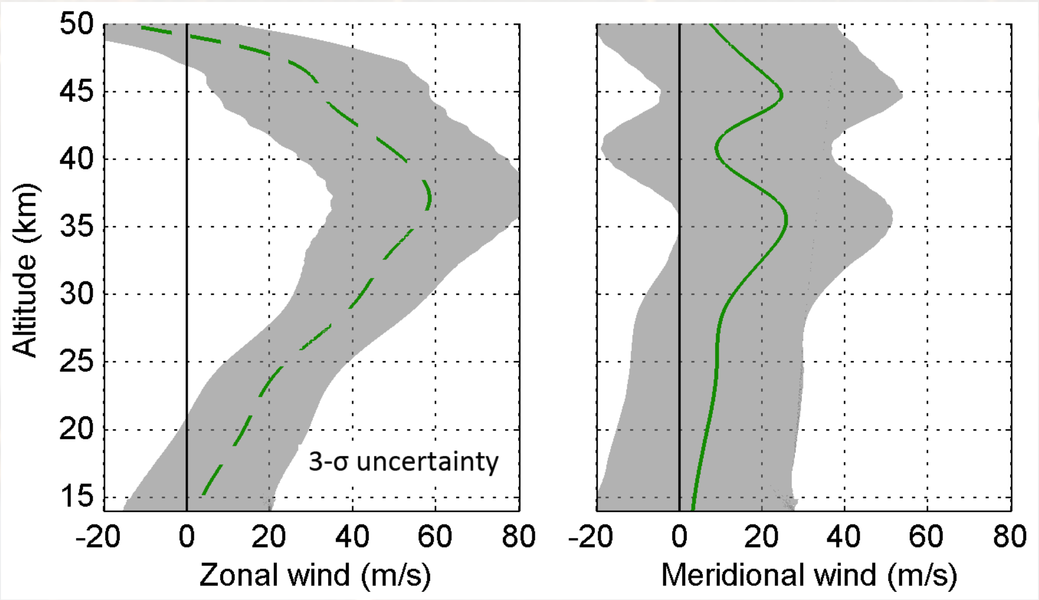
Can we retrieve the winds from the instrumented heat shield?



← the change in angles of attack and sideslip are accurately resolved by the least squares solver

Reconstructing the atmospheric winds

Wind components reconstructed from heat shield pressures



→ **A fair estimate of the winds is obtained**

Conclusions

- Atmospheric reconstruction requires a sufficiently accurate trajectory reconstruction: every IMU should contain gyroscopes

- Heat shield pressures can improve the density profiles, especially in 10 < Mach < 5. But an accurate pressure model is critical!

- A fair estimate of the winds was obtained from simulated heat shield pressures. Dealing with real heat shield data will be more challenging

Acknowledgements

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http://badc.nerc.ac.uk

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Future work

- Refine uncertainty estimates with Monte Carlo method
- Evaluate different heat shield pressure tap lay-outs
- Combine the IMU and heat shield instrumentation reconstructions using a 6-DOF extended Kalman filter
- 6-DOF trajectory simulation tool so that winds affect trajectory
- Perform an MSL case study when flight data becomes available
- Prepare for ExoMars EDM case study using simulation tools
- Exploit additional data sets such as radio communications and radar altimeters